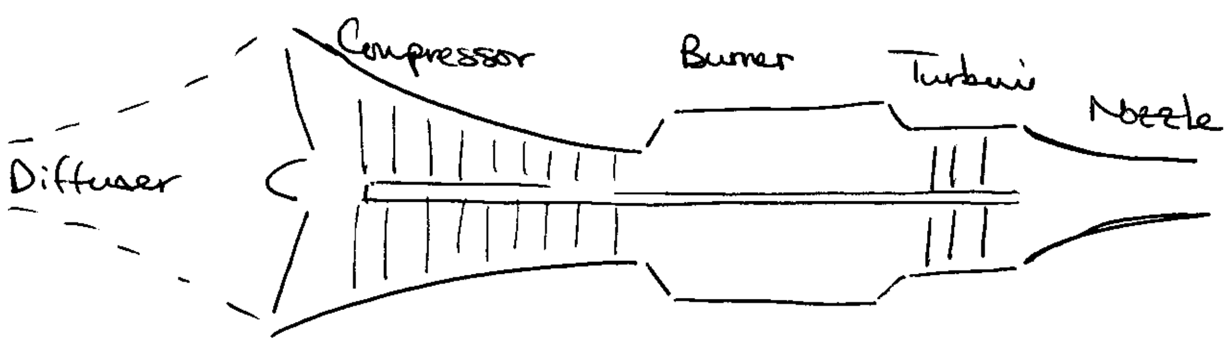
EM 320 - Exam #3 Name: SOLUTION

This Exam is Open Book, Open Notes.

Problem (1) (35 pts) A turbojet aircraft is flying at an altitude of 4900 m, where the ambient pressure is approximately 55 kPa and the ambient temperature is –13 C. The aircraft is traveling at a velocity of 283 m/s. The pressure ratio across the compressor is 16:1, and the maximum temperature in the cycle is 1200 K. Assume that the air entering the compressor has negligible velocity relative to the engine. The mass flow rate through the engine is 20 kg/s. Account to the variation of specific heats with temperature

a) Roughly draw the aircraft engine and label each component (5 pts)



b) Find the temperature of the air entering the compressor. (5 pts) (Variable Specific Heats)

$T_1 = 260°C$

$h_1 = 260.09 \frac{kJ}{kg}$ $\quad h_2 = h_1 + \frac{V_1^2}{2000} = 300.13 \frac{kJ}{kg} \rightarrow$ Table A-17 $T_2 = 300K$

$P_{r1} = 0.8405$

c) Find the rate of work done by the compressor (MW). (5 pts)

$P_{r2} = 1.3860$

$\frac{P_{r3}}{P_{r2}} = 16$

$P_{r3} = 22.18$

$\downarrow$

$h_3 = 662.5 \frac{kJ}{kg}$

$w_t = h_3 - h_2$

$w_t = -362.3 \ kJ/kg$

$\dot{W}_c = \dot{m} w_c$

$$\boxed{\dot{W}_c = -7.25 \text{ MW}}$$

$T_1 = 260\,°C$
$P_{r1} = 0.8405$

d) Determine the velocity of the air exiting the nozzle relative to the aircraft. Assume that the expansion in the nozzle is isentropic. (10 pts)

$w_T = w_c$ $\quad T_4 = 1200\,k$ $\quad \dfrac{P_{r4}}{P_{r6}} = \dfrac{P_{r3}}{P_{r1}} \rightarrow P_{r6} = 9.02$

$h_5 = h_4 - w_c$ $\quad h_4 = 1277.79$

$P_{r4} = 238$ $\quad h_6 = 513\ kJ/kg$

$h_5 = 915.49\ kJ/kg$

$V_6 = \sqrt{2000\,(h_5 - h_6)}$

$V_6 = 897.2\ m/s$

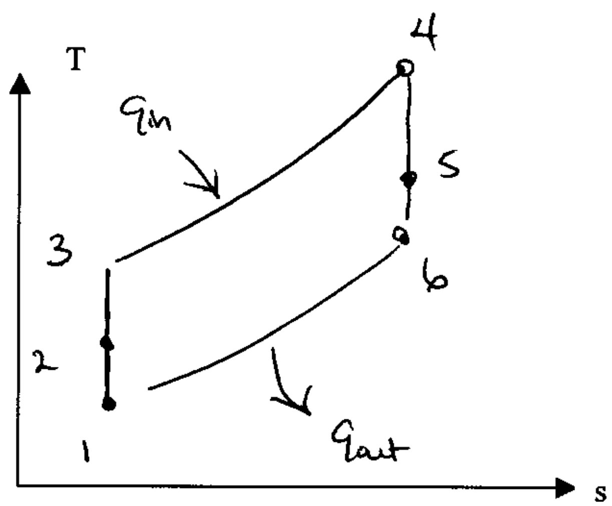
e) Calculate the thrust produced by this engine. (5 pts)

$F_T = \dot{m}\,[V_e - V_i]$

$F_T = 20\ kg/s\ [897.2 - 283]\ m/s$

$F_T = 12{,}283\ N$

f) Sketch this cycle on a T-s diagram. (5pts)



Problem (2) (30 pts) Compressed air is discharged from a large tank at 1 MPa through a converging diverging nozzle. The air inside the tank is initially at 300 K. The area at the throat of the nozzle is $5 cm^2$.

a) If the back pressure on the nozzle is atmospheric pressure of 100 kPa. Is the nozzle choked? In other words, is the flow at the throat sonic M=1? (5 pts)

$M = 1$ $\qquad$ $P^* = 528.3$

$\frac{P}{P_o} = 0.5283$ $\qquad$ Since $P_b < P^*$

Table A-15 $\qquad$ definately choked

b) The back pressure is now changed such that a normal shock exists at the exit of the nozzle. The flow prior to the shock wave has a Mach number of 2.2. Calculate the pressure on both sides of the shockwave. (15 pts)

$M = 2.2$ Table A-15 $\qquad$ $M = 2.2$ Table A-16 $\qquad$ * could also have used equations

$\frac{P}{P_o} = 0.09352$ $\qquad$ $\frac{P_y}{P_x} = 5.48$

$\boxed{P_x = 93.52 \text{ kPa}}$ $\qquad$ $\boxed{P_y = 512.5 \text{ kPa}}$

c) Determine the mass flow rate through the nozzle for the conditions described in part (b) (10 pts)

a) $$\dot{m} = \frac{A M P_o \sqrt{k/RT_o}}{\left[1 + (k-1)\frac{M^2}{2}\right]^{k+1/2(k-1)}}$$

$T_o = 300 K$
$R = 287 \ m^2/s^2 K$
$P_o = 1000,000 \ N/m^2$
$M = 1$
$A = 0.0005 \ m^2$

$\dot{m} = 1.1667 \ kg/s$

b) $\dot{m} = \rho V A$ $\qquad$ $\frac{T^*}{T_o} = 0.8333$ $\qquad$ $T^* = 250$

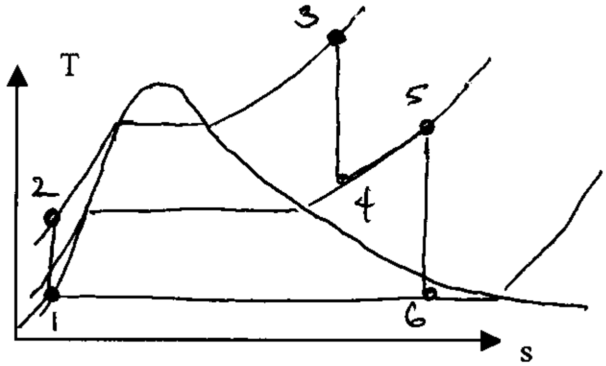
$\rho_o = \frac{P_o}{RT_o} = 11.61 \ kg/m^3$ $\qquad$ $\frac{\rho^*}{\rho_o} = 0.6339$

$\rho^* = 7.3628 \ kg/m^3$ $\qquad$ $c = \sqrt{kRT} = 316.9 \ m/s$

$\dot{m} = 1.1667 \ kg/s$

Problem (3) (35 pts) Consider a 100 MW steam power plant that has been designed to operate on an ideal reheat cycle. Steam enters the high pressure turbine at 10 MPa and 500 C and leaves at 1 MPa. The condenser operates at a pressure of 15 kPa. The quality of the steam entering the condenser is 90%.

a) Sketch this cycle on a T-s Diagram (5 pts)



$v_1 = 0.001014\ m^3/kg$

$h_1 = 225.94\ kJ/kg$

$h_2 = h_1 - \omega_p$

$h_2 = 236.06\ kJ/kg$

b) Calculate the specific work done by the pump (kJ/kg) (5 pts)

$\omega_p = -v_1 [P_2 - P_1] = -10.12\ kJ/kg$

c) What is the maximum temperature to which the steam can be reheated? [If you cannot find this temperature assume that the steam entering the low pressure turbine is 400 C for part d) and e)] (10 pts)

State 6

$P_6 = 15\ kPa$

$x = 0.9$

$s_6 = 7.283\ kJ/kg\,K$

$h_6 = 2361.7\ kJ/kg$

State 5

$P_5 = 1\ MPa$

$s_5 = s_6 = 7.283\ \frac{kJ}{kgK}$

Table A6 $\rightarrow$

$\boxed{T_5 = 345\ °C}$

$h_5 = 3147\ \frac{kJ}{kg}$

d) Determine the mass flow rate of steam in the cycle. (10 pts)

State 3

$P_3 = 10\ MPa$

$T_3 = 500°C$

$h_3 = 3373.7\ kJ/kg$

$s_3 = 6.5933\ kJ/kg\,K$

State 4

$P_4 = 1\ MPa$

$s_4 = s_3$

$h_4 = 2781.2\ kJ/kg$

$\omega_T = h_3 - h_4 + h_5 - h_6$

$\omega_T = 1377.8\ kJ/kg$

$\omega_p = -10.12\ kJ/kg$

$w_{net} = 1367.7\ kJ/kg$

$\dot{m} = \frac{\dot{W}_{net}}{w_{net}} = \frac{100{,}000\ kW}{1367.7\ kJ/kg}$

$\boxed{\dot{m} = 73.1\ kg/s}$

e) What is the thermal efficiency of the cycle? (5 pts)

$q_{in} = h_3 - h_2 + h_5 - h_4$

$q_{in} = 3503.5\ kJ/kg$

$\eta_{th} = \frac{w_{net}}{q_{in}}$

$\boxed{\eta_{th} = 39\ \%}$